Figure 1: *Aerial view of the VIRGO interferometer near Pisa, Italy. It consists of two 3 km long arms.*

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A Search for Gravitational Waves with VIRGO

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General Relativity is one of the most fundamental and beautiful physical theories. Yet, it is poorly tested, as compared to other fundamental physical theories as for instance quantum electrodynamics. One of the key features of general relativity is the dynamical nature of space-time itself: its curvature is a time-dependent quantity, and ripples of curvature can propagate through space with the speed of light. Such propagating curvature ripples are called gravitational waves (GW), and their existence is one of the most important, yet untested, predictions of this theory.

In our universe, GW are produced by unique astronomical events, such as mergers of pairs of black holes or neutron stars, and supernovae explosions. Gravitational waves can be used to probe the evolution of such compact objects. The data obtained by detection of GW are entirely independent of any observation in the electromagnetic spectrum. Therefore, they are likely to lead to unique information on the nature of these compact objects. Moreover, GW propagate almost unperturbed through essentially the entire universe. This makes it in principle possible to detect GW-signals emitted during the very early stages of the Big Bang. Measuring the amplitude of the waves at different frequencies should give information on matter at energies around 10^{18} GeV, a scale that will never be reached by men-made experiments.

The spectrum and amplitude of GW depend sensitively on the details of the Big Bang models, i.e. inflationary fields causing rapid expansion of the size of the universe, rapid collapse of cosmic strings, etc. [*dit is wat heel kort door de bocht, kunnen die inflationary fields wat nader uitgelegd? of zeg het wat simpeler*] Therefore, measurements of these properties of GW will represent the first direct test of Big-Bang models. Also, detection and further observation of GW would both provide important tests of the theory of General Relativity and would open a new window for astronomical observations of fascinating cosmic phenomena.

Since gravitational waves originate from sources many (millions of) lightyears away, their signal strengths at Earth are expected to be extremely weak. They cause relative displacements of free masses by distances that are a tiny fraction of the size of an atomic nucleus. Hence, enormous technological challenges have to be overcome in order to actually detect a signal. Large resources all over the world have been committed to building several types of gravitational-wave observato-

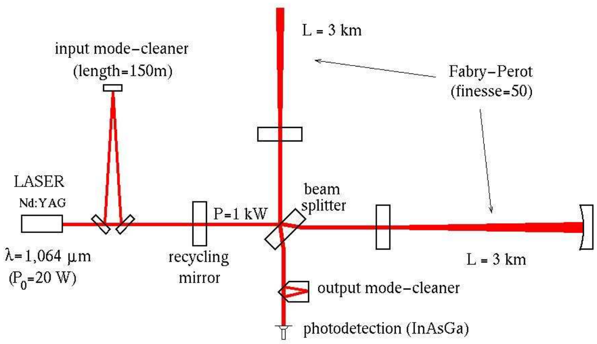

Figure 2: *Schematic outline of the VIRGO interferometer showing the main optical components. [kan eventueel over 2 kolommen]*

ries that are capable of detecting this weak but fundamental phenomenon.

NIKHEF has joined VIRGO, a Michelson-type interferometer with a base length of 3 km. It has been built by a French-Italian collaboration at Cascina close to Pisa, and is poised to start data taking by the end of 2006. Fig. 1 shows an aerial view of the two perpendicular arms of the interferometer. At the heart of VIRGO is an ultra stable ND:YAG laser of the newest generation with 20 W power and a wavelength of 1.064 mm; a 'recycling mirror' boosts the available power to several tens of kW and brings the shot noise (in strain-equivalent terms) to about 3×10^{-23}. The laser pulse is split and both pulses travel a number of times up and down an arm after which an interference pattern is created by rejoining the pulses of both arms. Each 3 km long arm contains a Fabry-Perot cavity (finesse 50) that increases the effective interference length to about 120 km. A passing gravitational wave would distort space locally and hence change the path length of each arm differently. The resulting change in the interference pattern can then be detected. Fig. 2 shows a schematic outline of the interferometer.

[*hier heb ik een overgangszin toegevoegd*] Since the GW signal is weak, noise is the big enemy of the VIRGO experiment. Seismic vibrations of the ground are billions of times larger than the subatomic distance variations induced by gravitational waves. In VIRGO the seismic isolation is achieved through a chain of suspended seismic filters made of triangular cantilever blade springs. The springs provide the vertical isolation while the compound pendulum provides isolation against horizontal motions. To further reduce the seismic disturbances, this chain is attached to an actively stabilized platform that compensates for very low frequency and large amplitude oscillations. It also provides a first stage of position control down to about one micron. A second stage of position control is achieved at the end of the suspension chain by a 'marionetta' from which the mirror and a 'recoil mass' are suspended by extremely fine wires. The ultimate mirror position control is obtained through very small forces [*is force hier het goede woord? of misschien feedback force?*] generated between the mirror and the recoil mass by sets of electromagnetic actuators.

[*hier heb ik een verbindende zinsnede toegevoegd*] Not only noise reduction, but also perfect alignment is absolutely crucial. It is achieved by taking out a small fraction of the light at the different mirrors and sending it to quadrant diodes. The output of these diodes can be used to maintain the alignment independent of drifts of the laser itself. NIKHEF took responsibility to improve over the present alignment capacities. In a first step, 14 new and improved electronics boards for the electronic read-out of the quadrant diodes are being built providing the needed parts and enhancing the present capabilities. [*dit laatse deel van de zin vind ik niet fraai, die needed parts lijken me overbodig, dus waarom niet : "... are being built that enhance the present capabilities"*] NIKHEF contributes to the alignment and thermal stabilization of the interferometer. [*deze zin staat er ook wat vreemd, het eerste deel over alignment kan m.i. weg, want heb je net in een hele alinea besproken, het tweede deel lijkt me iets nieuws, dus bijv. "NIKHEF also contributes to the thermal stabilization of the interferometer." eventueel gevolgd door " by building/providing/.... ..."*] In addition, NIKHEF searches for signals from (binary) pulsars. [*In deze laatste zin gaat het ineens over analyse lijkt me. Als dat waar is zou die zin wel wat uitgebreider mogen bijv. "NIKHEF actively participates in the (standard?) analysis of the VIRGO data. In addition, we search for signals from (binary) pulsars by .../ because ... ?*]

Gravitational-wave astronomy will be further developed by the satellite-based interferometer project, LISA. It will have three satellites positioned in orbit around the sun, trailing the Earth by some 20 degrees. The range of sensitivity of LISA is expected to reach down to gravitational waves of frequency 10^{-4} Hz. This will enable for instance the observation of the coalescence of massive black holes.